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GROUNDWATER SYSTEMS AND DRYLAND SALINITY IN A CATCHMENT NEAR BOHO, N.E. VICTORIA

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Abstract: An investigation of groundwater systems related to secondary dryland salinity was carried out between March and September 1982 in a catchment on the northern slopes of the Strathbogie Ranges. A shallow aquifer, ranging in depth from 12 to 20 m, discharges water at fresh and saline seeps. The aquifer is characterised by relatively high hydraulic conductivities and consists of waters which display chemical equilibria with albite. Underlying the aquifer is a deeper groundwater system which shows chemical equilibria with kaolinite and comprises materials of low hydraulic conductivity. The groundwater discharge areas have not increased in size for over 50 years. Assuming steady-state conditions, a water balance was carried out which suggests that the seeps result from an increased groundwater recharge of 20 mm caused by the reduction in transpiration following clearing of a native, deep-rooted forest.

Secondary soil salinity in dryland agricultural areas is now recognised as a major problem in Australia. Peck *et al.* (1983) report that an estimated 4 260 km² are severely affected. Detailed reviews discussing the cause of dryland salinity may be found in Peck (1978), Malcolm (1982) and Conacher (1982), and summarised on an Australia-wide basis by Peck *et al.* (1983). It is estimated that in Victoria at least 90 000 ha of non-irrigated agricultural land are severely affected by secondary salinisation (Jenkin 1981). Victorian salinity research has been summarised in general terms by Mitchell *et al.* (1978) and in more detail by Jenkin (1979).

The problem in Victoria was first recognised by Downes (1949) in a study of erosion in the northeast of the state. Subsequently, Cope (1958) suggested that salts of cyclic origin, as analysed by Hutton and Leslie (1958), were transported to the valley floor by shallow subsurface drainage or throughflow. Rowan (1971) presented the first systematic and detailed study of dryland salting in Victoria, from the northwestern region of the state. He recognised two groundwater systems responsible for salinisation, namely a locally perched body within aeolian sediments, and a deeper regional aquifer. Rowan considered that clearing of the native mallee vegetation was responsible for mobilizing salts stored within the profile. These salts were subsequently redistributed by groundwater and accumulated at the soil surface.

The relationship between salinity and hydrogeologic properties of the Riverine plains has been discussed by Macumber (1969, 1978). Macumber revealed that the capacity of the deep leads had been exceeded due to the increased recharge within catchment areas. This resulted in saline seeps being formed following the rise in groundwater levels to within the capillary fringe across substantial areas of the Riverine plains.

In 1973 the Northern Slopes Land Deterioration Project was initiated by the Victorian Soil Conservation Authority to investigate the processes of erosion and dryland salinity (Jenkin & Irwin 1975). Detailed research was to be conducted only in Ordovician sedimentary terrain. Essential principles established from the detailed investigation were used to interpret information gathered in other Victorian localities in which dryland salting was apparent. The report presented preliminary conclusions suggesting that clearing of native forests and their replacement with shallow-rooted annual pastures caused a marked decrease in evapotranspiration and a consequential increase in groundwater recharge.

Dyson and Jenkin (1981), Jenkin (1981) and Jenkin and Dyson (in press) subsequently presented the results of more detailed hydrologic studies. From an experimental catchment near Kamarooka, north of Bendigo, they suggested that saline groundwater, discharging at the break of slope between the Ordovician upland front and the Riverine alluvial plains, originates from increased annual recharge derived from the cleared slopes. Jenkin (1981) and Jenkin and Dyson (in press) have further shown that saline groundwater discharge is primarily the result of an upward movement of groundwater below saline seeps. This mechanism of groundwater discharge appears common in studies of dryland salting in Australia (Nulsen & Henschke 1981).

In the Shire of Violet Town, at the junction between the Riverine plains and the bedrock uplands, dryland salting was recognised as a significant agricultural problem by the local community (George 1982a). Consequently a catchment was chosen at Boho, 8 km southeast of Violet Town, in which hydrologic studies were carried out to determine the processes involved in dryland salinisation under geologic and geomorphic conditions different from those studied by Dyson and Jenkin at Kamarooka.

GEOLOGY AND LAND-USE

The study area is located on the northern slopes of the Strathbogie Ranges (Fig. 1). These slopes represent the junction between the Riverine alluvial plains and the uplands described by Jenkin (1981). The steep nature of the junction zone is geologically controlled by the late Devonian, igneous, quartz-biotite-hypersthene dacite (White 1953). The surface catchment has an area of 50 ha, a relative relief of approximately 200 m, and is

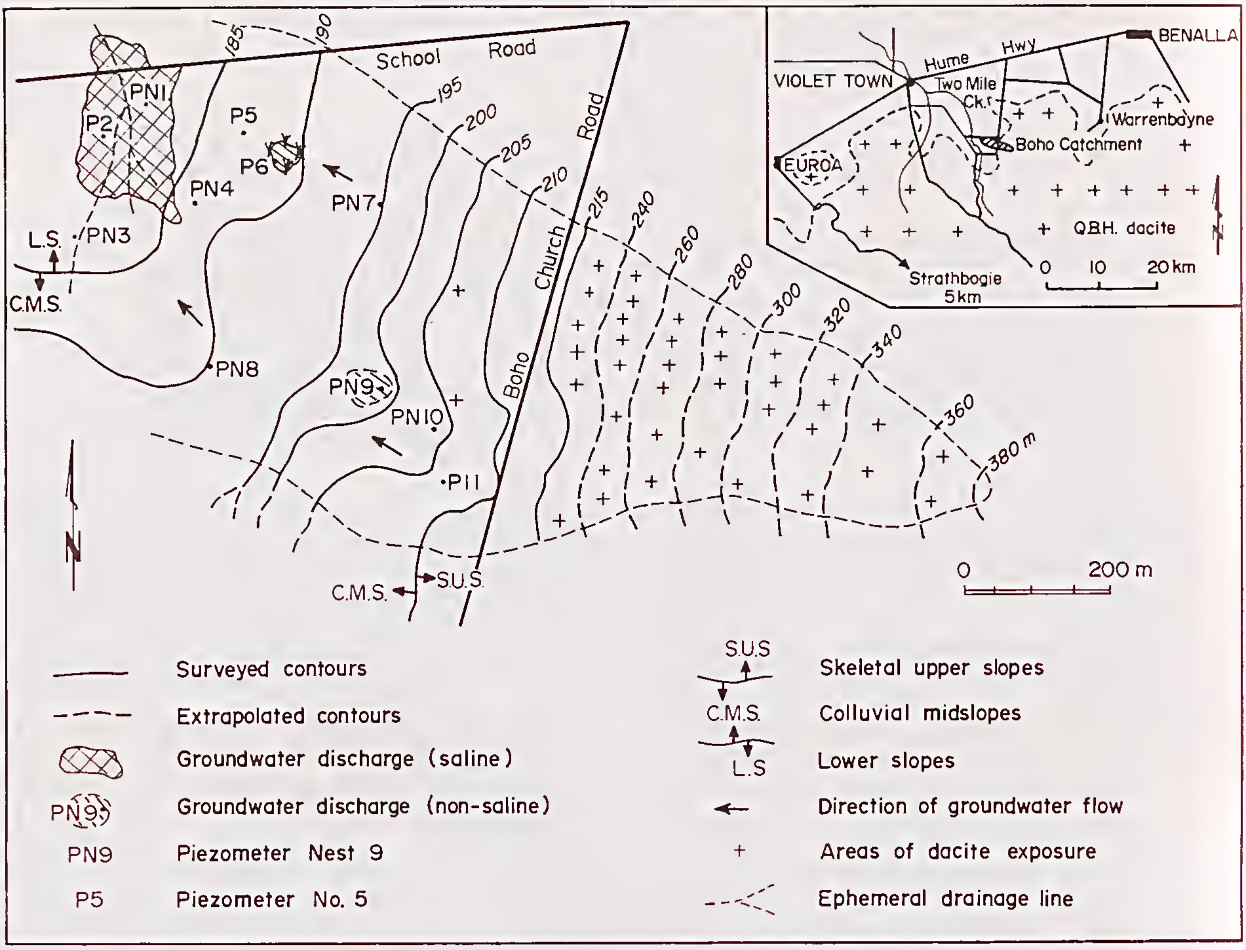


Fig. 1—Boho experimental catchment, N.E. Victoria.

the western face of a large spur which protrudes from the Ranges (Fig. 2). The salt-affected land and its local catchment, are located within the Two Mile Creek drainage basin. Its incised, ephemeral stream is located nearly a kilometre from the salt-affected area.

Clearing of the catchment occurred between 1875 and 1890, and only scattered remnants of the red box (*E. polyanthemos*) forest remain. Limited regrowth of sub-canopy species has occurred on the upper slopes, which are too steep for most agricultural activities. Pastures have remained unimproved and are dominated by onion grass (*Romulae rosea*) and capeweed (*Arthothea calendula*) at the expense of native species. The area of dryland salinity has remained stable for at least 50 years, being first noticed in approximately 1920.

METHODS

A network of 27 piezometers was located in the catchment to monitor the groundwater systems. To assess the hydraulic properties of the saturated materials piezometers were installed in nests of three. The piezometer nests consist of a shallow (<5 m below ground surface) intermediate (<10 m) and deep (<20 m) PVC tube slotted over the lower two metres for each depth interval.

Piezometer nests were located at lower, middle and upper slope sites, in such a pattern that groundwater isopotential maps could be prepared. All nests were west of the Boho Church Road as near-surface rock prohibited drilling east of the road.

Topographic and isopotential maps were prepared from surveyed spot-heights located throughout the lower- and mid-slopes of the catchment. On the upper slopes, east of the Boho Church Road (Fig. 1), surface catchment information was extrapolated from the Euroa 1:100 000 mapsheet (8035: edition 1), aerial photographic interpretation and field observations.

A standard 10 cm bucket auger was used to install the shallow piezometers in the saturated zone. Soil samples were collected at 0.5 m intervals to an average depth of four metres. Each sample was described using the techniques presented by Northcote (1971). Where possible samples were collected below this depth from the 'flights' of the *Gemco* power auger which was used to install the intermediate and deep piezometers. Im-

Fig. 2—The photo shows both the saline (centre-top) and non-saline (centre) groundwater discharge areas.

mediately drilling ceased, an appropriate length of slotted and capped 40 mm PVC pipe was inserted, the annulus around the pipe backfilled with washed sand screenings, and finally sealed above the slotted length with bentonite pellets. The remainder of the annulus was then filled with excavated materials and again sealed with a bentonite cap at the soil surface.

Values of saturated hydraulic conductivity were obtained from each piezometer using the Hvorslev, single well 'rate of rise' bailing technique (Hvorslev 1951). This method is recommended for application in materials with relatively low permeability (Hendry 1981).

Soil and water samples were analysed for electrical conductance (EC-mSm^{-1}), using the techniques discussed by Loveday (1974). The sampling of 1:5 aqueous extracts was conducted in April, 1982, while four water samples were analysed from each piezometer between April and August. A further 16 samples were analysed for Na, K, Mg, Ca, Fe, Cl, HCO_3, CO_3, NO_3 and SO_4. Hardness, as percent $CaCO_3$, as well as pH and electrical conductance were determined. An attempt was made to understand the thermodynamic and chemical equilibria conditions within the groundwater systems from the results of the chemical analyses. The method involves deriving ion activities according to the Debye-Huckel equation, and plotting appropriate values on equilibria-stability diagrams produced by Nesbitt (1977).

Values of mean annual precipitation and annual potential evaporation were extrapolated for the Boho catchment from field stations operated by the Bureau of Meteorology at Violet Town, Warrenbayne and Strathbogie. These stations are located within 20 km of the Boho catchment (Fig. 1).

RESULTS

Climate

Precipitation at the catchment was estimated to have a mean annual value of 650 mm, while the potential annual evaporation rate was 1530 mm. A distinct seasonality exists with high evaporation rates and low rainfall in summer, while in the four winter months rainfall exceeds the potential evaporative demand. Although 860 mm of rain was recorded during 1981, the study period of 1982 received less than 30% of the mean annual rainfall. Field observations indicated that rainfall events of sufficient intensity and duration to produce surface runoff did not occur.

Geomorphic Units

Three geomorphic units were identified within the catchment. The units are described as the upper, mid and lower slopes, with each type being separated by distinct gradient changes (Fig. 1). The lower and mid slope units comprise a complex association of alluvial

and colluvial sediments. The upslope soils appear to be developing *in situ*, although field observations identified some colluvial activity on the steeper slopes.

The upslope skeletal soils are coarse textured and uniform, grading from stony loams to loamy sands. These slopes are steep, ranging in slope angle from 6° to 24°. Rock outcrops and small cliffs are common features of this slope unit. Midslope colluvial soils are predominantly brown, gradational sandy clays while limited areas of yellow duplex profiles were also recognised near piezometer nest 6 (PN6). The midslope unit ranged in slope angle between 2° and 6°. The lower slope unit (<1°) occurs below the break of slope in the valley floor which corresponds with the salt-affected area. In this zone soils are brown, uniform, silty or sandy clays. The salt-affected area is extensively gullied and displayed salt efflorescence during most of the study period.

Groundwater Systems

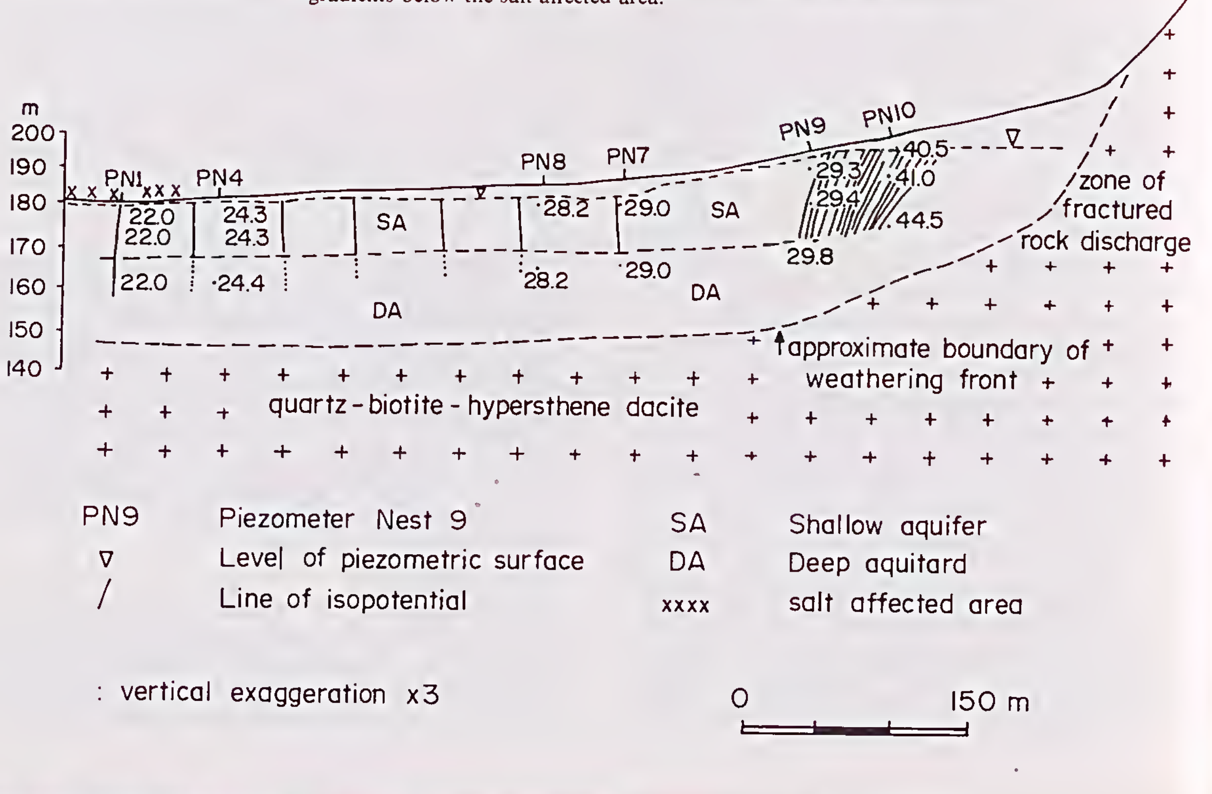
The hydraulic properties of the materials which comprise the groundwater systems are relatively anisotropic. The two zones can be distinguished by their differences in hydraulic properties, mineralogy, soil texture and physical conditions implied while drilling. The shallower materials, located to depths of 12 m in the lower slopes and to greater than 20 m at PN9, consist of sandy and silty clays. These sediments were saturated to near the surface in the salt-affected area (PN1) and at the upslope groundwater discharge area (PN9). It is considered that most of the groundwater within the shallow aquifer originates as discharge from the fractured dacite.

The deeper materials, consisting of heavy textured clays, form the deep groundwater system. This material is located at depths greater than 20 m at PN10 and greater than 12 m at PN1 and PN3. The total depth of the deep groundwater system is unknown; however, evidence from local bores suggests that weathering depths may range from 20 m to as much as 40 m in similar geomorphic environments.

Hydraulic Conductivity

The hydraulic conductivities calculated from each piezometer reflect the textural dichotomy of the substrates as previously identified during drilling and sampling. The variation between the calculated values of saturated hydraulic conductivity from the deep and shallow groundwater systems exceeds two orders of magnitude. Hydraulic conductivities obtained from shallow and intermediate piezometers within the colluvial midslopes have representative values of 4.0×10^{-2} m/day. Limited evidence suggests that values derived from the intermediate piezometers have slightly higher hydraulic conductivities (6.0×10^{-2} m/day). However, the relative variation is insignificant when compared with the deep groundwater system. Mean hydraulic conductivities calculated from the deeper system provide a representative value of 5.0×10^{-4} m/day. The cumulative evidence suggests that an aquitard exists below a more permeable aquifer.

Fig. 3—The flow-net illustrates the predominance of vertical gradients in the upper slopes and lateral gradients below the salt-affected area.



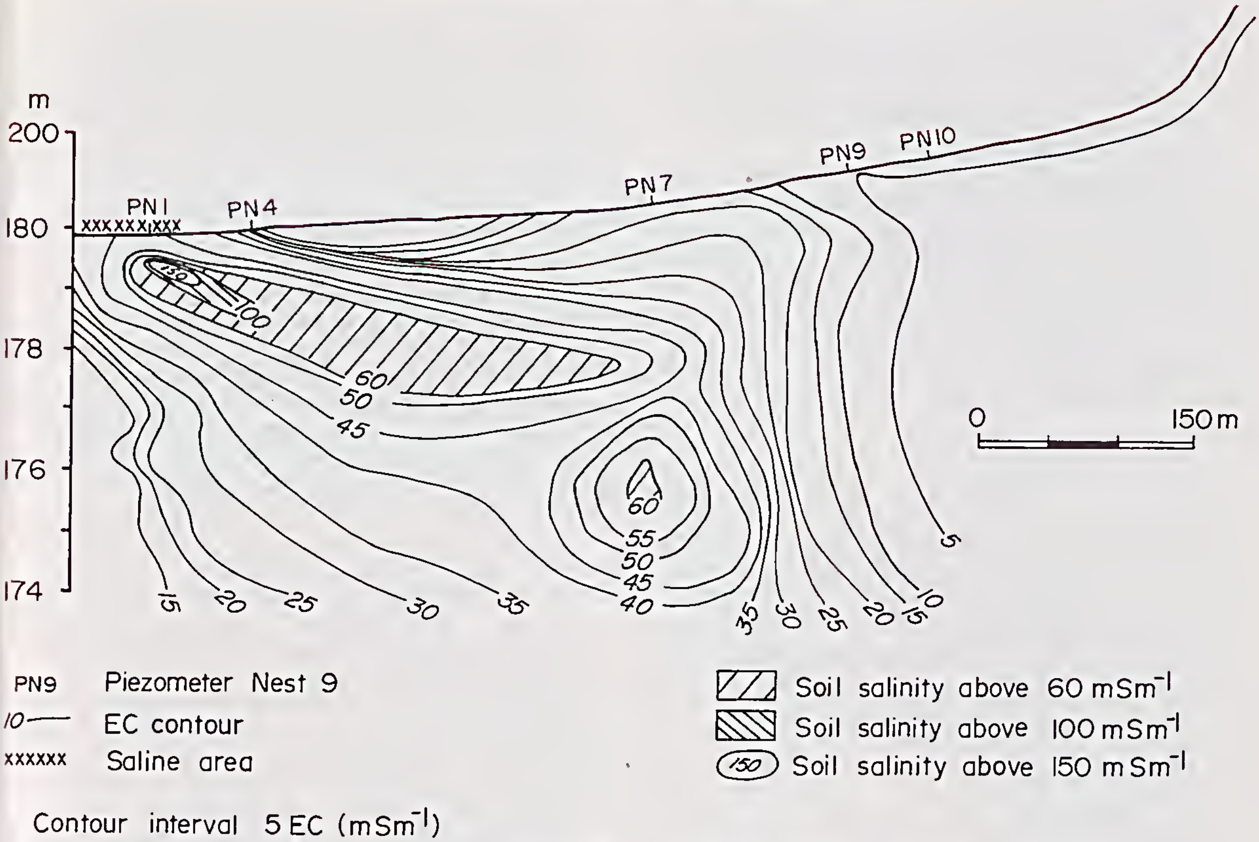


Fig. 4—Soil salinity contour profile showing the increase in soil salinity towards the groundwater discharge area.

Hydraulic conductivities ($3.0 \times 10^{-2} - 3.0 \times 10^{-3}$ m/day) obtained from the deep piezometers at the break of slope between the upper and midslopes (PN9 and PN10) reflect both the coarser material encountered, and the dominance of the shallow aquifer characteristics deeper in the profile and at higher levels in the catchment.

Hydraulic Gradients

Lateral hydraulic gradients from the deep and shallow groundwater systems are dissimilar. Lateral gradients within the shallow aquifer approximate those of the surface topography, being 0.05 upslope and decreasing to 0.01 at the salt-affected area. In the deep groundwater system, lateral gradients near the break of slope between the upper and midslopes are very steep (0.07), reducing to 0.02 in midslopes and 0.01 in the lower slopes.

In order to present graphically the hydraulic properties of the catchment, a flow-net was constructed from the potentiometric data (Fig. 3). The flow-net indicates that groundwater discharge from the fractured dacite is under steep hydraulic gradients near PN9 and PN10. However, a uniform gradient exists in the mid and lower slopes. The flow-net further indicates that lateral flow is dominant in both the deep and shallow groundwater systems, and that no upward pressure potential exists below the salt-affected area.

Soil Salinity

Soil salinities increase towards the salt-affected area (Fig. 4), and are concentrated towards the surface. The electrical conductivity (1:5 aqueous extracts) of samples ranges between 1.0 mSm^{-1} in the skeletal soils of the upper slopes and 150 mSm^{-1} near the surface at the salt-affected area. Conductivities of samples taken in the deep groundwater system range between 8.0 and 16.5 mSm^{-1} across the entire catchment, with the higher conductivities observed in the lower slopes. In contrast, values between 30 and 50 mSm^{-1} are common in the shallow groundwater system near the salt-affected area.

Three salt profile forms were delineated within the shallow soils (< 5 m) of the catchment. The first displays a major zone of concentration, or bulge, below the soil surface. The second displays a steady increase with depth and the third a steady decrease with depth.

Groundwater Salinity

Within the shallow aquifer a marked increase in electrical conductivity was observed towards the salt-affected area, peaking at 1460 mSm^{-1} at PN4 (Fig. 5). Conductivities within the salt-affected area are

significantly lower (200-300 mSm^{-1}). A similar trend was observed within the deep groundwater system. In this zone two peak values occur at PN4 (450 mSm^{-1}) and PN7 (560 mSm^{-1}), but are significantly lower in all other locations, including the salt-affected area where salinity remains less than 100 mSm^{-1}.

Chemical speciation of the waters revealed that Na, HCO_3 and Cl are dominant in both the shallow and deep groundwater systems. Mg and Ca are minor species in all samples, with the exception of PN7, while SO_4, NO_3, CO_3 and K display consistently low concentrations. The importance of bicarbonate is reflected in the alkalinity of the groundwaters, which range from pH 7 to 10. Groundwater discharge at the soil surface has changed typical soil pH values from pH 5.1-6.4 to pH 8-9.

GROUNDWATER BALANCE

In order to quantify the hydrologic processes within the catchment an instantaneous groundwater balance was calculated. Several important assumptions were made on the basis of the experimental and field observations. The calculations assume that all the water is distributed by the shallow aquifer, and that the deeper system is not a source of groundwater discharge to the salt-affected area. Discharge by evaporation from a shallow water-table within the capillary fringe (and groundwater underflow) was considered to be in equilibrium with groundwater recharge, since the area of salt-affected land has remained stable over 50 years. This assumption considers that the area of groundwater discharge within the catchment is directly proportional to the area of groundwater recharge within the catchment.

Given these assumptions, a direct relationship may be drawn between recharge and discharge such that:

$$A_D \text{ (ha)} \times D \text{ (mm)} = A_R \text{ (ha)} \times R \text{ (mm)} \qquad (1)$$

where D = discharge, A = recharge area or discharge area and R = recharge.

Groundwater flow towards the salt-affected area was calculated from Darcy's Law, using the Dupuit-Forchheimer assumptions at PN3 and P5. The results show that 3.21 Ml move towards the salt-affected area annually. The value of groundwater discharge at the surface was obtained by subtracting the annual quantity of flow which moves laterally beyond the discharge area. This flow component was estimated from known values of hydraulic conductivity and cross-sectional area, and was small (0.36 Ml yr^{-1}). In this case the hydraulic gradient was considered to reflect the surface topography between the salt-affected area and the Two Mile Creek, as no piezometers had been installed down-aquifer from the salt-affected area. Groundwater discharge at the salt-affected area was therefore calculated to be 2.85 Ml yr^{-1}.

The discharge of groundwater at the salt-affected area can easily be accounted for, since it represents only 4.4% of the total potential annual evaporation rate. Discharge was also apparent from two other locations within the catchment. Surface water within the 'spring-fed' excavations was considered to evaporate at the potential rate, while discharge at PN9 was estimated at the fraction of the potential rate used above. Using the steady-state equation presented above (equation 1), it can be shown that approximately 20 mm of annual groundwater recharge is needed to maintain the discharge at the salt-affected area.

DISCUSSION

In reviewing the cause of saltland in Western Australia, Nulsen and Henschke (1981) and Malcolm (1982) reported that groundwater discharge is the result of evaporation from a shallow water-table. However, in these reviews it is noted that discharge results from upward hydraulic gradients from partially or semi-confined aquifers. In these cases it is argued that a potentiometric gradient forces water towards the surface. This feature is also noted in many physiographic regions of Victoria (Jenkin 1981).

At Boho no evidence was obtained to suggest that groundwater discharge at the salt-affected area is maintained by vertical hydraulic gradients. It is therefore considered that the presence of a saline area within the catchment is simply the result of a shallow water-table from which evaporation-induced, capillary rise occurs. However, the upslope groundwater discharge area (PN9) appears to be the result of steep vertical, hydraulic gradients of the sort mentioned by the authors noted above. At this location no salt-affected area exists as the groundwater salinity appears too low.

The assumption that 'catchment equilibrium' exists between recharge and discharge is based on the salt-affected area having remained stable for at least 50 years. On this basis it was assumed that a new hydrologic equilibrium had been developed between 30 and 50 years after clearing. This condition of equilibrium was seen to reflect a reduction in evapotranspiration resulting from the clearing of the deep-rooted native forest, and its replacement by shallow-rooted pasture species. It is therefore reasonable to infer that nett groundwater recharge has increased as a result. The development of a salt-affected area in this case follows once water-tables rise to a level at which discharge takes place at the same rate as recharge.

The calculation of the rates of groundwater discharge (and hence recharge) are empirical first approximations. At Boho the existence of lateral flow within an unconfined aquifer suggests some difficulty in stating categorically that all water is discharged from the salt-affected area. It is conceivable that vertical hydraulic gradients may develop during seasonal periods of high potential evaporation near the surface of the shallow aquifer in the salt-affected area. However, neither the stratification of nested piezometers nor the research timetable allowed these factors to be considered. It is therefore concluded that in the light of the information available, based on interpolated hydraulic parameters, groundwater underflow leaving the catchment was a minor feature in the groundwater balance.

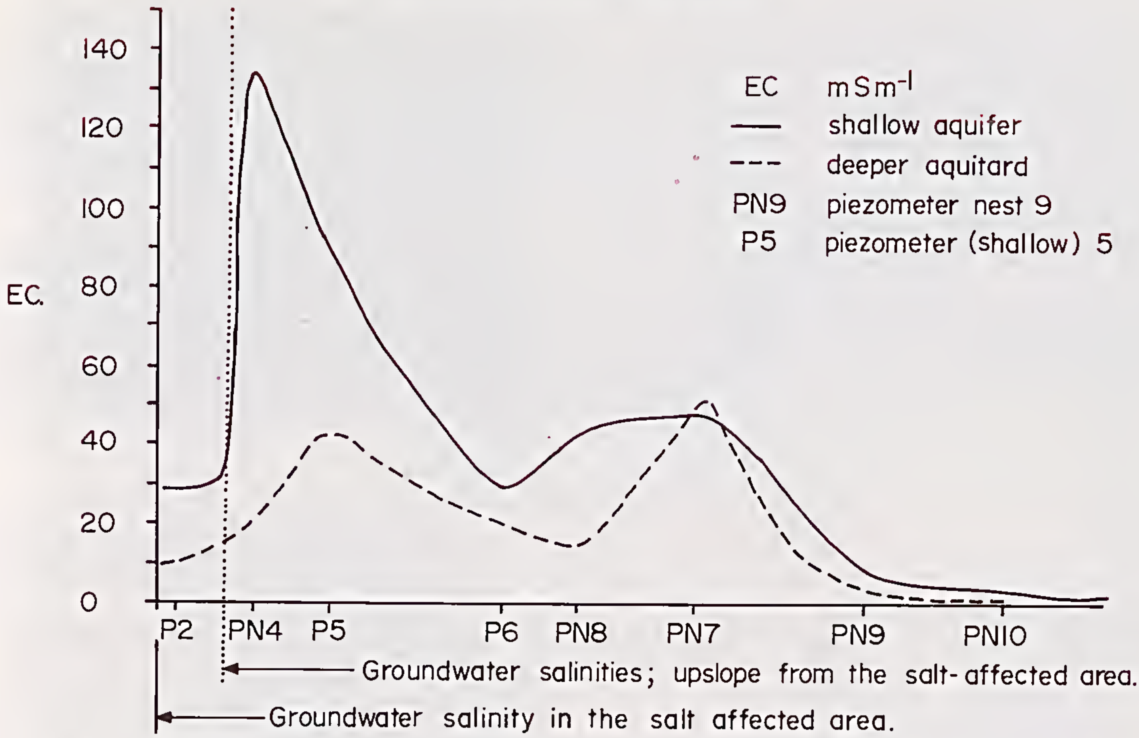


Fig. 5 — Groundwater salinity in each system increases towards the salt-affected area. The deeper system is considerably less saline than the shallower system.

The calculations would also appear to be validated since the potential evaporation rates create the ability for groundwater discharge to occur throughout most of the year. The results from the catchment groundwater balance would also appear to be similar to those obtained by Jenkin and Dyson (in press) at Kamarooka, north of Bendigo in central Victoria. At this location Jenkin and Dyson (in press) report that groundwater discharge is the result of 17 mm (5.7% of the annual potential evaporation rate) annual recharge. At Boho recharge rates were calculated to be approximately 20 mm, of 4.4% of the annual potential evaporation rate.

In order to provide further support for the contention that a distinctive two aquifer system exists the chemical composition of each groundwater system was compared. The technique applied required that ion-activity coefficients be computed from each chemical analysis, using the Debye-Huckel equation. It is recognised that this method can only be considered as a first approximation when delineating aquifer geochemistry; however, the results obtained were informative and deserve some comment. The equilibria conditions were inferred by analysing the results graphically, using Nesbitt's (1977) stability fields (Fig. 6). From these plots it may be inferred that the shallow system possesses groundwater that exhibits chemical equilibria between sodium-beidellite and albite whereas the deeper system indicates equilibria between kaolinite and sodium-beidellite (P. Dyson pers. comm.). Further analysis of the thermodynamic nature of the aquifers was not considered, as the results correlated with the measured hydraulic parameters and clearly indicated the anisotropic nature of the groundwater systems.

Although the complexities of groundwater movement within the catchment require further analysis, several other similarities and differences were observed between the conditions under which dryland salting occurs at Kamarooka, discussed by Dyson and Jenkin (1981), Jenkin (1981) and Jenkin and Dyson (in press), and at Boho.

Within the Boho and Kamarooka catchments saline groundwater discharge was observed at the break of slope between valley alluvium and bedrock hills. However, at Boho, non-saline groundwater discharge was also apparent at the break of slope between the colluvial and upper-slope units. Discharge at this point is the result of steep vertical gradients, reflecting flow from the fractured-rock zone. However, unlike Boho, saline groundwater discharge in the lower slopes at Kamarooka is the result of strong vertical gradients below the seep. At Kamarooka the different geology, flatter topography and groundwater flow characteristics are believed to be significant in explaining the dissimilarities observed.

The similarity noted above between the recharge rate and the actual annual evaporation rate suggests that the differences which exist between the geologic and

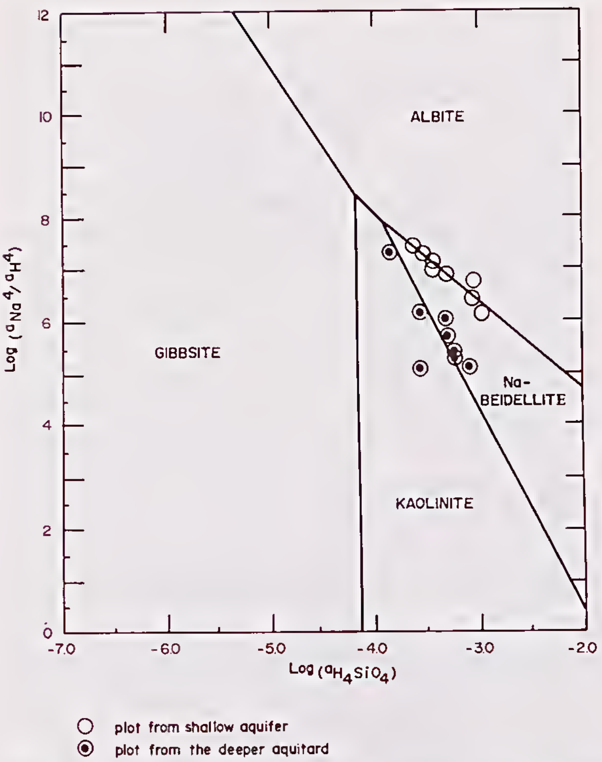


Fig. 6—The figure illustrates the different chemical characteristics of each groundwater system.

geomorphic environments are less significant than the hydrologic effects of reduced evapotranspiration following the clearing of native vegetation.

CONCLUSIONS

Two distinct groundwater systems were found within the Boho catchment. The volume of groundwater transported by the shallow aquifer was found to be 200 times greater than that of the deep groundwater system. Soil and water salinities vary between the fresher deep system, and the more saline shallow waters, increasing in both cases towards the salt-affected area. The anisotropic nature of the groundwater systems was further verified from the contrasting values of hydraulic conductivity and the differing chemical conditions within each system. Dryland salting within the catchment is produced by the evaporation of saline water (200-300 mSm^{-1}) from a shallow water-table (< 1.6 m). Where fresh water (< 30 mSm^{-1}) is discharged no soil salinisation occurs, although similar surface characteristics were observed. Groundwater discharge at the soil surface by evaporation appears to be balanced by approximately 20 mm annual recharge to the aquifer.

The implication of low recharge values is important for catchment management procedures. Future forest or agricultural controls need therefore only increase water use in the recharge areas by a similar amount to restore productivity at the salt-affected area. At Boho it would appear that beneficial results could be obtained by applying management controls to the skeletal soils in the upslope area. Future research should look to defining more precisely areas of preferential recharge so that management techniques might only disrupt a small proportion of the total area currently used for agriculture.

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